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CIRCADIAN RHYTHMS AND SUSTAINED OPERATIONS

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SUMMARY

Sustained operations necessarily conflict with the circadian system in several ways: changes in the habitual work-rest cycle, shifts in meal- or sleep-timing, intense activity during night hours, sleep deprivation and disruptions of the normal synchrony between body functions and environment. When these rhythm disturbances affect performance, they become operationally significant. Their consequences are discussed and factors are described which influence the range of performance oscillation. Of particular operational relevance are motivation, sleep and physical exercise. Under certain conditions they can help to overcome deficits in performance and periods of diminished efficiency.

The temporal structure of the environment in 24-hour periods corresponds to the periodic fluctuations in physiological, performance, and behavior functions of the human circadian system (Figure 1). Often different rhythms exhibit divergent curves, as for instance with respect to the temporal positions of minima and maxima, or to the magnitude of their amplitudes. During total isolation from environmental Zeitgebers, biological rhythms oscillate with spontaneous period lengths deviating from 24 hours; in addition, different functional systems, such as body temperature and activity, may oscillate with divergent frequencies, a phenomenon which has been labelled "internal desynchronization" (Wever, 1979). Persistence of fluctuations under constant conditions and the phenomenon of internal desynchronization suggest the conceptual understanding that circadian rhythms are endogenous in origin, self-sustained and controlled by more than one "internal clock". Several models have been developed to describe the circadian system. The non-hierarchical multioscillatory model appears to offer the best concept to explain the presently known facts (Aschoff, 1978).

Under normal conditions biological rhythms fluctuate with periods corresponding exactly with the length of the natural 24-hour day (Figure 2). This habitual synchrony is achieved, by the influence of environmental time cues or "Zeitgebers" (Aschoff, 1962). For plants and animals these are in particular the oscillations of light and temperature resulting from earth rotation. For man much evidence was gained that knowledge of clock hours and daytime-related social activities appear to be of more influence than the natural light-dark cycle (Wever, 1982). Thus, meal timing, work-rest patterns, and in particular sleep-begin and sleep-end act as preponderant synchronizers for the human circadian rhythm.

Sustained operations interfere with these Zeitgebers in one or another aspect and therefore give rise to rhythm disturbances. Conflicts principaly result from the following conditions: (1) The period length of synchronizing rhythm is changed, (2) the controlling force of time cues is weakened or vanishes completely, and (3) phase shifts occur in Zeitgeber oscillations. The first condition relates to the fact that sustained operations necessarily cause period extension of habitually synchronizing rhythms, such as work-rest or sleep-wake cycles. The second condition, for instance, appears always as an

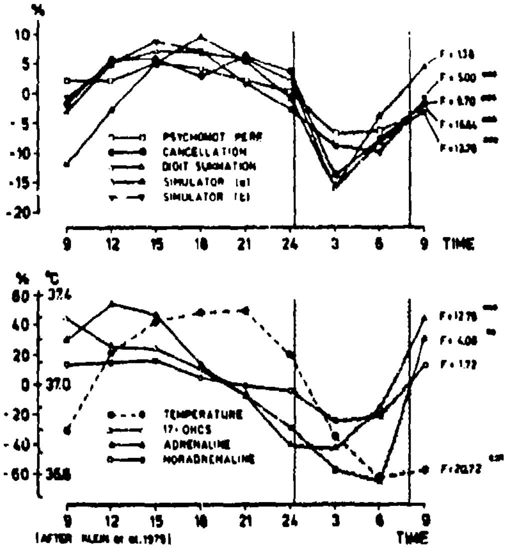

Figure 1: Circadian rhythms of different performance functions and physiologocal variables. (F-values for significance of within-day variation).

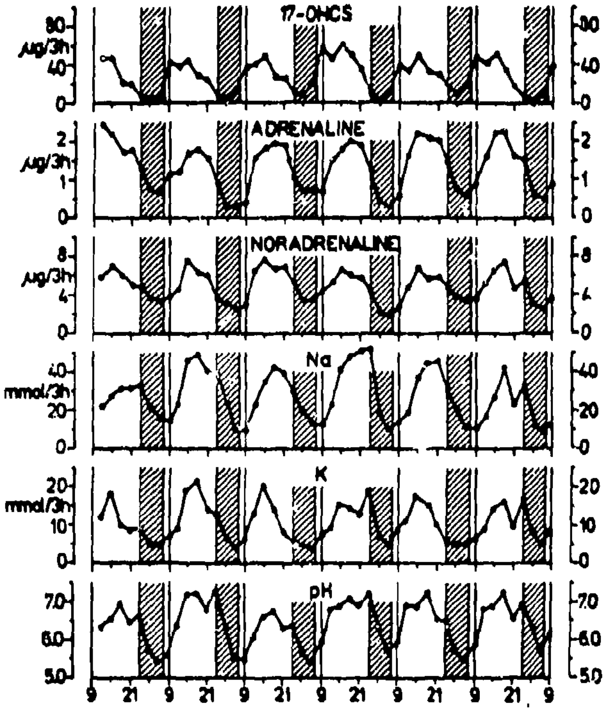

Figure 2: Circadian rhythms in the urinary excretion pattern of hormones and electrolytes in a group of 8 subjects over 6 24-hour periods.

unevitable consequence of sleep deprivation, since sleep-begin and -end as well as sleep itself belong to the strongest agents of controlling endogenous rhythmicity. It also occurs in any other situation of partial or total deprivation from external periodic inputs, such as being socially isolated or being confined to closed systems. The third condition can be observed whenever time-zones are crossed or synchronizer rhythms are phase delayed or advanced, as by shifting meal- or sleep-timing, for instance (Graeber, 1982). In the aviation environment of sustained operations all three conditions become effective, singly or in combination, but producing always the same effect, a disturbance of the biological timing system. When these rhythm disturbances affect physical and mental performance, they become operationally significant (Klein & Wegmann, 1980). Since sleep is part of the circadian system, if is obvious that also the consequences of sleep disturbances and sleep deficit have to be considered (Johnson & Naitoh, 1974; Nicholson & Stone, 1982).

Disturbances of circadian rhythms become manifest by changes in the parameters defining their regular oscillation, i.e. period, phase, amplitude, and 24-hour level. Basically, they are induced through modulations of the interrelationship between the internal and external timing systems. They are the direct consequences of alterations in the rhythm characteristics of the environment, be it a phase shift or a deprivation of Zeitgebers, which may again be total or partial, occurring naturally or being manipulated arteficially. They also result, when the biological system is shifted in relation to a stable environment, thus disrupting the habitual synchrony between both systems, as it happens, for instance, in industrial shiftwork after switching from day- to nightwork.

Probably the most extensive body of data with significance for the exploration of the human circadian system was obtained from studies in deep caves, underground bunkers and isolation chambers. These facilities allow an almost perfect isolation of an individual from natural time cues normally entraining his circadian rhythm to a period of 24 hours. Furthermore, they present the possibility to substitute the habitual timing system by one or several arteficial Zeitgebers which then can be easily manipulated (Wever, 1979). The most prominent form of manipulation has been the introduction of constant light or constant darkness. The response of the human circadian system is the well-known free-running state which is charaterized by the peristence of the oscillation, but with a different cycle length, most subjects showing a spontaneous period close to 25 hours. Out of more than 150 subjects with presumable free-running rhythms, only two subjects showed periods shorter than 24 hours (Wever, 1982).

In the free-running state all measured variables usually oscillate synchronously, i.e. different rhythms are internally synchronized. Some of the subjects, however, show internal desynchronization: Different variables oscillate with different cycle lengths. Most frequently, rhythms of rectal temperature hold a period close to 25 hours, whereas activity rhythms alter their periods considerably and demonstrate cycle lengths in the range between 30 and 40 hours. In long-term cave experiments the existence of even longer activity periods was observed, amounting to 48-50 hours. Because they enclose 2 circadian cycles, they have been labelled "bi-circadian" or, more approperately, "circa-bi-dian" (Wever, 1979). Some discussion has been raised as to whether this phenomenon could be utilized in the military field. Indeed, a period of about 36 hours of sustained performance may have strategic advantages for military operations. However, only some individuals show the capacity to free-run with a circa-bi-dian activity rhythm. Upon returning to the natural 24-hour system they rapidly convert their cycle to "normal". Thus, it seems rather difficult to achieve such a prolongation of the cycle length. Summarizing the results, obtained from controlled environment facilities with constant timegiver conditions, it can be concluded that several stimuli were identified that have the potontial to modify autonomous circadian rhythms of man. These are as different as light intensity, temperature, psychical stress, and social contacts. When applied in a constant manner during the free-running state, they all result in a lengthening of the autonomous period, except for electromagnetic fields which ware shown to shorten it (Wever, 1979).

By alteration of the external stimuli in a cyclic manner, artifical Zeitgebers were installed, permitting investigations of various problems with practical implications, such as strength and capacity of different time cues, as well as range of periods to which the circadian system can be synchronized (Aschoff, 1978). From the results it can be concluded that human circadian rhythms can be synchronized by artificial Zeitgebers, but with periods varying only within a limited range of entrainment: Beyond 22-28 hours they desynchronize. There are different kinds of external periodicites generating different strength of control: For man, physical Zeitgebers are less effective than those with a component of social contact. Physical synchronizers exhibit also smaller ranges of entrainment than social time cues. Sudden shifts of the Zeitgebers usually induce corresponding phase alterations of the biological rhythms. However, the circadian system does not follow the shift immediately, but instead shows a certain "inertia" in achieving a new rhythm. Extent and duration of this transient state of rhythm disturbances are different in rhythms of different variables.

The military significance of the disturbances in circadian rhythmicity are debatable (Hartman et al., 1974). There is much evidence, however, that daytime-related oscillations are among the endogenous and exogenous determinants for man's functional capacity of physical and mental activity. It has been shown that circadian rhythmicity does not only control physiological functioning at rest, but also the response of the body to load, thus involving performance and efficiency (Klein & Wegmann, 1980). For many years already, late night sections have been charcterized as the "minimum of readiness for efficiency" and as the "hours of diminished resistance". For animals it was shown that even death and survival in a hostile environment were a function of circadian phase. But probably due to poor methodology and inappropriate measuring techniques equivocal results created scepticism as to the genuine and significant relation between time of day and mental performance. Today, there is enough evidence that circadian rhythmicity does not only control the primary physiologic functioning of the human organism, but also its behaviour under operational stress (Naitoh, 1982). During the hours when tonic physiologic levels are set for sleep rather than wakefulness, the "readiness" for mental performance is reduced. In the laboratory under experimental conditions, the nocturnal "low" of perceptual-motor responses differs considerably from the diurnal "high". Apart from probably minor and unimportant variations, performance rhythms rise during the day to a plateau between 12:00 and 21:00 hours and then decline to a minimum which usually occurs at 03:00 to 06:00 during night. Folkard (1982) recently has pointed to the fact that this is not generally true, at least not for different memory loads. Immediate memory tends to decrease over the day, but delayed retention is superior in the afternoon or evening.

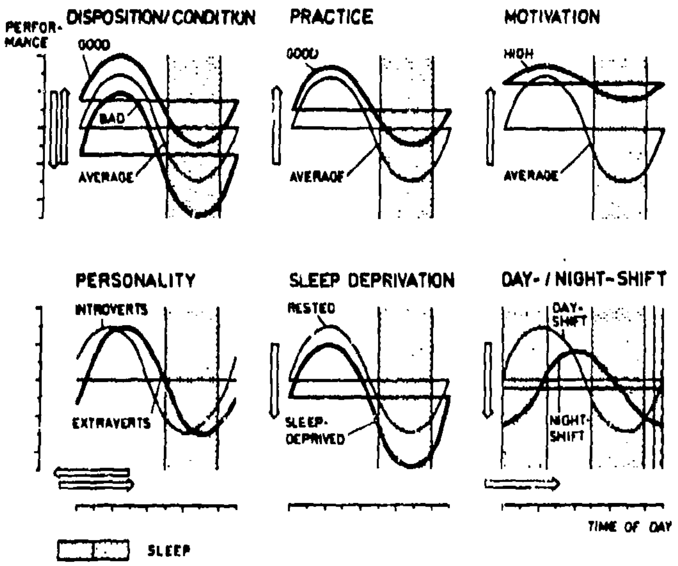

Figure 3: Schematic illustration of modifications in performance rhythms through various factors.

There are several factors that are able to modify mental performance rhythms (Klein et al., 1976): sleep, task variables, personality, motivation, physical activity, and changes in work-rest cycles (Figure 3). Most of them influence the range of oscillation and therefore have operational significance. Of particular interest are motivation, sleep and physical activity, since they can be directly controlled. Motivation reduces circadian oscillation of mental performance through "extra effort". Together with workload (that is the stress imposed by the task) it determines the extent of cycling in so far, that the range of oscillation is low if motivation is good or the task relatively simple. On the other hand, the difference between maxima and minima is more pronounced if motivation is low or the task very complex. In context with the workload, the reduction of the circadian amplitude during practicing and its increase during sleep deprivation can be understood as effects of relative workload changes. High motivation, no doubt, can overcome performance dificits at night. However it must be remembered that aircrews engaged in wartime sustained operations are functioning closer to biological and psychological limits than under normal schedules and therefore may be more vulnerable to influences affecting their performance. This is of particular relevance, if the adverse effects are accumulating, as during sustained operations is unevitable, due to prolonged wakefulness, sleep deprivation, and a hostile environment. Wartime threat on the other hand, may be a source of motivation that is almost unkown from training and simulation (Haslam, 1981).

Sleep loss probably is the most critical effect of sustained operations. It also affects circadian oscillation of performance efficiency, but at the same time leads to an impairment of the overall level with increasing sleep deficiency. The extent of performance degradation depends on the actual phase of the circadian cycle it coincides with (Alluisi et al., 1977). The effect of fatigue is obviously compensated - at least in part - by the increasing level of arousal during the day. In contrast, operational fatigue will enhance the depression of alertness naturally occurring at night. From these findings it becomes clear that, whenever possible, management of human operations should prevent a coincidence of the final section in the sustained activity with the nocturnal low of behavioral rhythms.

The effects of sleep deprivation are psychological rather than physiological (Haslam, 1981). Injections of sleep sections into a period of sustained operations are beneficial, even if their amount is very small. Again, for crew management these findings are of significance, in particular with respect to reinforced crew operations.

Finally, physical activity may influence mental performance through changes in the level of arousal: Light to moderate physical work is improving it, heavy work has the opposite effect. As could be demonstrated, this effect depends also on the time of day as well as on task specifity. A physical load which was about 1/3 of the maximum aerobic capacity, increased the scores of a visual-motor coordination test in the morning and afternoon, but not in the late evening and early night. However, the same exercise regimen impaired performance in a memory test. The results may be explained by differences in the relative load of physical activity: the load was probably beyond the optimum of arousal for memory functions, but not for the psychomotor coordination performance at the specific times of day (Klein & Wegmann, 1980).

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DISCUSSION

DR A RIECK (GE)

I believe that you stated that although fatigue increased progressively during a 48 hour period without sleep, there was a small increase in alertness at the beginning of the second day without sleep. Is this so? Is there any work which attempts to correlate these changes in subjective fatigue with objective physiological measures?

AUTHOR'S REPLY

In answer to your first question, yes the circadian rhythm of fatigue was superimposed on the fatigue caused by the prolonged wake period. No, we did not obtain any correlations between fatigue scores and physiological functions.